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This program consisted of experimental and theoretical studies of the physics, tecnnology, and spectroscopy of extreme ultraviolet (XUV) and soft x-ray lasers. It is a continuation of several predecessor programs. The overall objective of our work is to develop a class of lasers whose wavelengths span the 100 Å to 1000 Å spectral region. Major accomplishments are summarized and resulting publications listed.

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Research Studies on Extreme Ultraviolet and Soft X-Ray Lasers

Final Technical Report
For the Period
23 November 1985 -- 22 November 1988

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Section 1

Introduction and Summary of Work

This program consisted of experimental and theoretical studies of the physics, technology, and spectroscopy of extreme ultraviolet (XUV) and soft x-ray lasers. It is a continuation of several predecessor programs. The overall objective of our work is to develop a class of lasers whose wavelengths span the 100 Å to 1000 Å spectral region. We are also interested in developing incoherent, laser driven, hard x-ray sources which operate on a femtosecond time scale, and which could be used both for time resolved x-ray spectroscopy and, ultimately, for the pumping of solid state, micron-dimension, x-ray lasers.

Our work on XUV and soft x-ray lasers began about ten years ago with the use of high peak power microwaves to produce metastable, non-autoionizing core excited species. The work has proceeded on both the spectroscopic and laser fronts. Section 2 lists the principal accomplishments in these areas, but we note that there have also been unexpected and especially fruitful interconnections between these areas: for example, our proposal for the super-Coster-Kronig Zn system, which initiated the recent successes in the 1000 Å spectral region, to a large part resulted from the availability at Stanford of the Cowan atomic physics code. This code had been brought up to aid in our understanding of Column I and II quasi-metastable systems. Similarly, the recent successes of depletion spectroscopy have resulted from our use of laser produced x-ray excitation. This type of excitation, which is now key not only to our program, but also to programs at AT&T Bell Laboratories (Silvfast and Wood) and at Berkeley (Falcone), resulted from our attempts to produce larger densities of Li metastables, ionic and atomic, for store-and-transfer laser systems.

This three year contract has been a particularly successful one. Though on the surface, the principal accomplishment of this program would seem to be the construction and operation of a fully saturated (extrapolated small-signal gain of exp 83) 96.9 nm laser in neutral Cs, probably the more significant accomplishment is the invention of the geometry that was used to make this laser. This geometry solves a problem that has long plagued our program: how to use laser-produced x-rays as an excitation source distributed over a long length, while maintaining the laser power density on target at the necessary minimum value. We developed and demonstrated a grazing-incidence grooved-target geometry that produces an effective traveling-wave plasma excitation source. This will be increasingly important at shorter wavelengths.

This unique geometry was also a key element in our earlier operation of the 108.9 nm Xe Auger laser, also at very high gain and fully saturated. Using only 3.5 J of 1064 nm pump energy, we attained a small signal gain of exp(40). When fully saturated, this laser produced about 20 μJ in a 50 psec pulse, with a beam divergence of 10 mr.

Other principal accomplishments of the laser portion of the program include the demonstration of large gain at 130.6 nm in the prototype super-Coster-Kronig Zn system of Mendelsohn and Harris, and the observation of gain at 90.7 nm in Kr. We note that the first demonstration of gain in both the Xe and Kr systems was accomplished by R. Falcone and his students at the Janus facility at Livermore.

The key accomplishment of the spectroscopic portion of our work has been the development and demonstration of a technique which we have termed depletion spectroscopy. This technique allows a single visible laser to be used to define the core-excited manifold of atoms and ions. This technique also allows the measurement of autoionizing times which are sufficiently long that their Lorentzian width lies well under the combined Doppler–hyperfine structure; in fact, recent work has shown that this technique is completely independent of this structure.

Recently, new approaches and technology have been developed for the amplification and compression of picosecond and femtosecond optical pulses. This technology, when combined with the traveling-wave geometry mentioned above, bodes well for the development of lasers in the 100 Å–1000 Å spectral region. We have done theoretical studies of mixed species targets for enhanced, short pulse incoherent x-ray production. We also began the construction of a high-power femtosecond time-scale laser amplifier system.

Finally, we have developed a new theory that shows a population inversion is not required to obtain laser amplification. It shows that if two upper levels of a four level laser system are purely lifetime broadened, and decay to an identical continuum, then there will be an interference in the absorption profile of lower level atoms, but this interference will be absent from the stimulated emission profile of the upper level atoms. It is therefore possible to have a substaintial gain cross section at frequencies where the absorption cross section is zero, and to obtain laser amplification under conditions where the lower level population greatly exceeds the upper level population. Such nonreciprocal gain–loss profiles may occur naturally in XUV and x-ray laser systems or may be synthesized using artificially layered materials.

Section 2

Contributions of Current and Predecessor Programs

Much of this work was jointly sponsored by other agencies. More details on these items can be found in the publications listed in Section 3.

- Our work on metastable store-and-transfer began in 1975 with the proposal and first experimental demonstrations of laser-induced dipole–dipole, dipole–quadrupole and charge-transfer collisions.

- In 1977, the anti-Stokes radiation source was proposed and analyzed in the context of a two-photon blackbody.

- The anti-Stokes source was used to take the $3p$ absorption spectrum of neutral potassium at a resolution of $1.5\,\mathrm{cm}^{-1}$. This is the highest resolution ever obtained in this region of the spectrum.

- A class of quartet–doublet laser systems was proposed; the emission spectrum of neutral Li near 20 nm was taken, and the quartet and doublet manifolds of Li were experimentally connected for the first time.

- Microwave, and later hollow-cathode technology, was used to produce metastable populations and to demonstrate several new types of core-excited spectroscopy. In one of these experiments the Grotrian diagram of core-excited Na was defined for the first time.

- The laser-produced plasma method of creating high densities of core-excited metastables was proposed and demonstrated.

- Using an impulsive electron source, produced by laser-produced x-rays, we demonstrated that levels that are imbedded in a continuum are not unusually sensitive to electron de-excitation.

- The ideas of shake-up and super-Coster-Kronig lasers were suggested.

- The concept of quasi-metastability was suggested and verified in several experiments.

- The method of core-excited depletion spectroscopy was suggested and used to define much of the $4p^5$ manifold of neutral Rb. It was found that the autoionizing times within this manifold are much longer than was first expected.

- Following the initial work of R. Falcone at Livermore, we observed and optimized gain for the Auger systems Xe ($\lambda = 108.9\,\mathrm{nm}$), Zn ($\lambda = 130.6\,\mathrm{nm}$), and Kr ($\lambda = 90.7\,\mathrm{nm}$).

- A new traveling-wave grazing incidence geometry was invented and used to construct a saturated 108.9 nm laser. This laser was pumped with 3.5 J of 1064 nm radiation, and had an output energy of 20 μJ in a 50 psec pulse.

- We improved the traveling-wave geometry to make it truly synchronous and constructed a 96.9 nm laser in Cs that has an extrapolated small-signal gain of exp(83) in a total length of 17 cm.

- Experimental studies of pre-pulsing laser plasma targets indicate that the necessary pump energy for lasers such as the 108.9 nm Xe Auger system can be reduced by a factor of three.

- We showed analytically that the use of special targets should make it possible to convert about 0.1% of high power, short pulse, laser energy to incoherent x-ray radiation in the vicinity of several angstroms, thus creating an x-ray source with a power density of $10^{15}\ \mathrm{W\,cm^{-2}}$.

- A new theory was developed that shows it should be possible to make lasers without an inversion.

Section 3

Publications Supported

1. K. D. Pedrotti, D. P. Dimiduk, J. F. Young, and S. E. Harris, "Identification and Oscillator Strength Measurement of the 109.1 nm Transition in Neutral Cs," *Opt. Lett.* **11**, 425–427 (July 1986).

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